

## EFFECT ON PERTURBED AREA OF THE FLOW AROUND A SPHERE DUE TO A CHANGE IN THE REYNOLDS NUMBER

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### ABSTRACT

*The goal of this paper is to explain and observe the effect of Reynolds number on the perturbed area of the fluid and the flow separation angle of the flow around a sphere. Reynold's number is, in brief, a dimensionless number – a ratio, taking into consideration the inertial and viscous effects of a fluid. The paper delves into the branch of fluid mechanics in physics, establishing a relationship between the Reynolds number of the fluid and the perturbed area of the flow around a sphere and the flow separation angle. Data including the perturbed area and the flow separation angle was recorded using a simulation and evaluated to come to a conclusion. The paper deduces that as the Reynolds number of the fluid increases, the flow separation angle decreases. Moreover, as the Reynolds number increases, the perturbed area of the fluid increases, however, the symmetry of the perturbed area decreases.*

**KEYWORDS:** Reynolds Number, Effect on Perturbed Area & The Flow Around a Sphere Due

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### Research Question

How does the finite value of Reynolds number of the liquid affect the perturbed area and the flow separation angle given that the type of liquid and nature of the object is constant throughout the experiment?

### INTRODUCTION

Reynolds number (Re) is the single ratio which takes into account the inertial and viscous forces within a fluid, such that it anticipates flow patterns for example, whether a flow is laminar or turbulent. This dimensionless number, developed in 1883 by Osborne Reynolds, is concerned with the fluid mechanics aspect of physics. Needless to say, its application in the industry extends vastly, including but not limited to, aerodynamics such as in wind tunnels, water pumps and pipes and the designing and functioning of water features such as fountains.

Mathematically, the Reynolds number formula is as follows:

$$Re = \rho v L$$

Where:

Re = Reynolds number

$\rho$  = Density of the fluid

v = Flow speed (velocity)

L = Characteristic linear dimension

$\mu$  = dynamic viscosity of the fluid

Several differences in characteristics of fluids from viscosity to flow velocity stem from variations in their Reynolds numbers. This paper is intended to determine the extent of the effect of the Reynolds number of a fluid on the flow separation angle as well as the area of the disturbed laminar flow around the sphere for Reynolds numbers that range from 1 to 500.

The research makes use of a simulation of the flow around a sphere at finite Reynolds number that uses the Galerkin method to build the lineation, and a real life experiment of the same to allow for a thorough demonstration of the effect of Reynolds number on the two mentioned variables and to establish a relationship between them.

## Theory

### *Reynolds Number*

Objects with low masses are driven by viscous forces instead of inertia due to less resistance to change in motion. Inertial force is the force which causes the liquid to flow and this force is caused by the difference between the ends of the pipe, whereas the viscous force would resist the inertial force.

Note: If 2 different types of liquid (different density) flow through geometrically same pipe will have the same Re value...for example when water has 1350 Reynold's number its magnitude to turn from streamline or laminar flow to turbulent flow and when oil flows through the congruent geometry of the pipe will also have 1350 as its point where it turns from laminar flow to turbulent flow.

It is the ratio of forces of inertia and viscous which has no dimension.

Reynolds number is found out by the formula:

$$NRe = vd/u$$

Reynolds number = density/velocity/diameter/viscosity

A fluid when flows are in the form of layers or laminations. This flow of liquid which does not cause disturbance on the layers are called laminar flow or viscous flow. As the flow rate increases, velocity increases and the viscous flow changes to critical flow and then to turbulent flow, disturbing the form of laminations or the layers of liquid.

This is where Reynold's number comes in. It is a numerical figure which has no specific dimension or shape, to define it: It is the ratio between the inertial forces to viscous forces and is significant to provide a description of the liquid's transport.

$$Re = \text{inertia forces} / \text{viscous forces}$$

For example when a ball or any object is placed between the flowing water and is used to identify whether the liquid is in a laminar flow or turbulent flow.

laminar flow has Reynolds number value less than 2000

critical flow is between 2000 to 4000

turbulent flow is more than 4000.

### Concepts

There are different units for Reynold's number.

Customary units:  $92.24 \frac{Q}{(vD)}$

$Q$  – flow rate, bbl/day

$D$  – internal diameter, in

$v$  – kinematic viscosity, cSt

SI units:  $353,678 \frac{Q}{(vD)}$

$Q$  – flow rate, m<sup>3</sup>/h

$D$  – internal diameter, mm

$v$  – kinematic viscosity, cSt

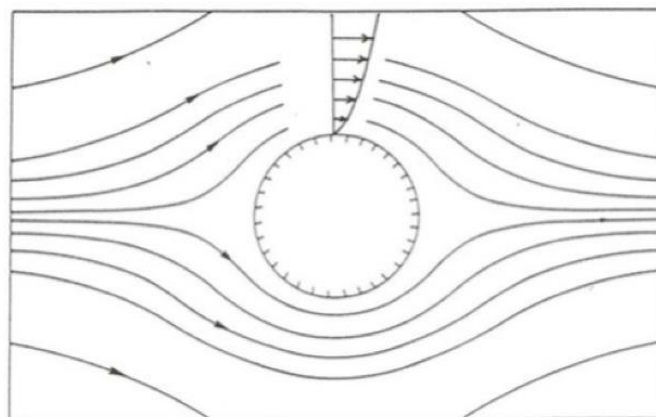
$Re = \text{inertia forces} / \text{viscous forces}$

At smaller Reynolds numbers i.e.  $Re < 1$ , the pattern is identical front to back (as in the above picture).

The flow lines are straight and uniform far from the front of the sphere but deflected as they pass around the sphere.

Important note, at low Reynolds numbers, as the distance from the sphere increases, the flow lines are more spaced out at the mid-section of the sphere due to viscous retardation, therefore there is less fluid velocity as there is less crowding of flow lines. At higher Reynolds numbers, the zone of retardation decreases in area significantly, thus the effect of crowding to increase velocity is offset less by higher viscous retardation.

Flow past sphere at high Reynolds numbers.



**Figure 1**

As  $Re$  increases, flow separation gradually develops and flow regime changes mainly due to viscous effects. Pressure and viscous forces share the same importance for a flow regime to be affected by flow separation effect, pressure forces can exceed viscous forces.

Even before complete development of flow separation, the drag coefficient deviates from stokes law, after complete development of flow separation, the drag coefficient shows no relationship to Stoke's law.

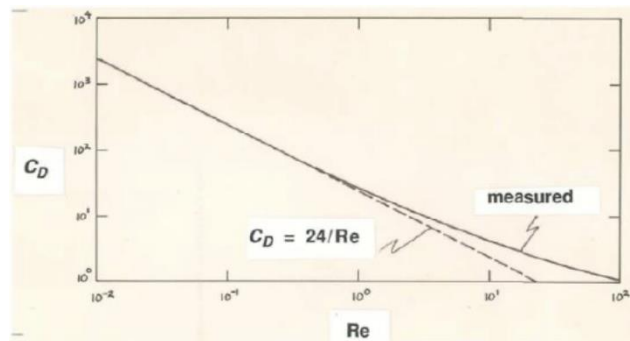


Figure 2

Flow regime - distinctive patterns of flow described by the Reynolds number

Flow regime is affected by flow conditions, e.g. diameter of sphere, velocity of fluids, kind of fluid as all these factors influenced the Reynolds number.

In (A) at  $Re < 1$ , streamlines show a symmetrical pattern front to back, and the flow velocity gradually rises away from the surface of the sphere. At lower Reynolds numbers, there is no well-defined boundary layer.

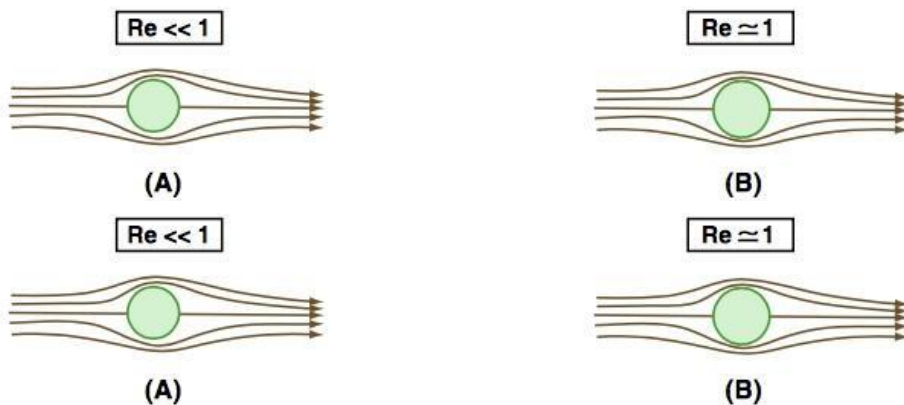


Figure 3

At  $Re \sim 1$ , the picture is about the same (B) as (A), but the streamlines converge more slowly at the back of the sphere than they diverge at the front. This change in the pattern of flow is when the front-to-back pressure forces increase more rapidly than predicted by Stokes law in this range of  $Re$ .

When flow separation develops in (figure C) (at  $Re \sim 24$ ), The point of separation is closer to the rear of the sphere, and a ring eddy forms attached to the rear end of the sphere (flow within the ring eddy is regular and predictable therefore not turbulent).

However, as  $Re$  increases, the point of separation moves towards the side of the sphere and starts oscillating becoming unstable.

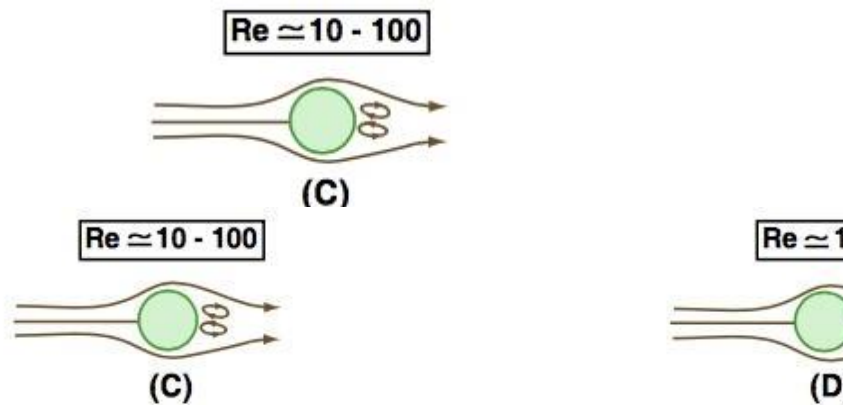


Figure 4

At  $Re$  in the range of hundreds, the ring eddy is cyclically shed from behind the sphere to drift downstream and decay as another ring eddy forms (at  $Re$  values of this range, turbulence starts to develop. In this range of  $Re$  values, the turbulence is mainly developed in the zone of strong shearing created by the flow separation after which it spreads downstream).

As  $Re$  progresses to a few thousand, several turbulent eddies form in the turbulent wake (figure F).

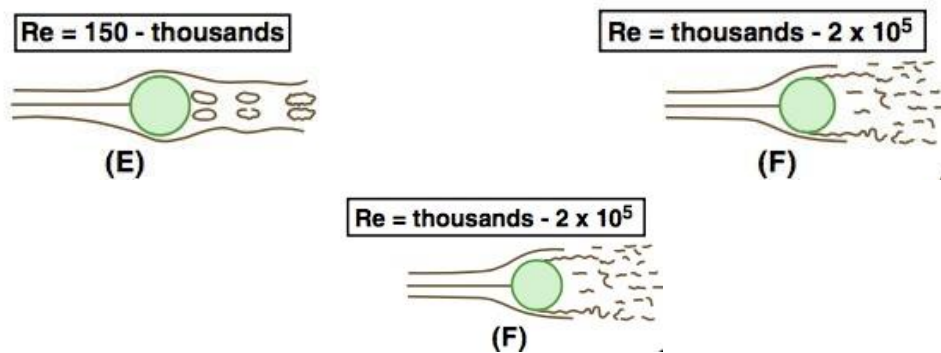


Figure 5

From 1000 - 200000  $Re$ , the flow pattern shows little change. The flow separation is about 90 degrees from the front stagnation point and there is a fully developed turbulent wake. Any drag observed is due to the pressure distribution on the sphere surface with a minor amount of viscous shear stress. (Drag coefficient remains same in this range of  $Re$ )

Beyond 200000  $Re$ , the boundary layer becomes turbulent before flow separation takes place, the flow pattern changes.

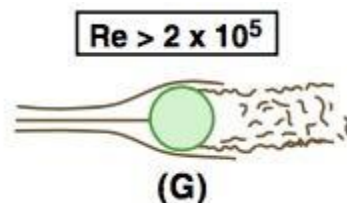


Figure 6

Laminar separation is when flow separation takes place when the boundary layer is laminar. Turbulent separation is when flow separation takes place when the boundary layer is turbulent upstream of separation.

Turbulent separation takes place farther around the rear of the sphere at 120 to 130 degrees from the stagnation point. The drag coefficient drops to 0.1 as turbulent wake contracts compared to its size when the separation is laminar, the pressure on the sphere is low within the separation region and acts over a smaller area and the pressure itself in the region is not as low.

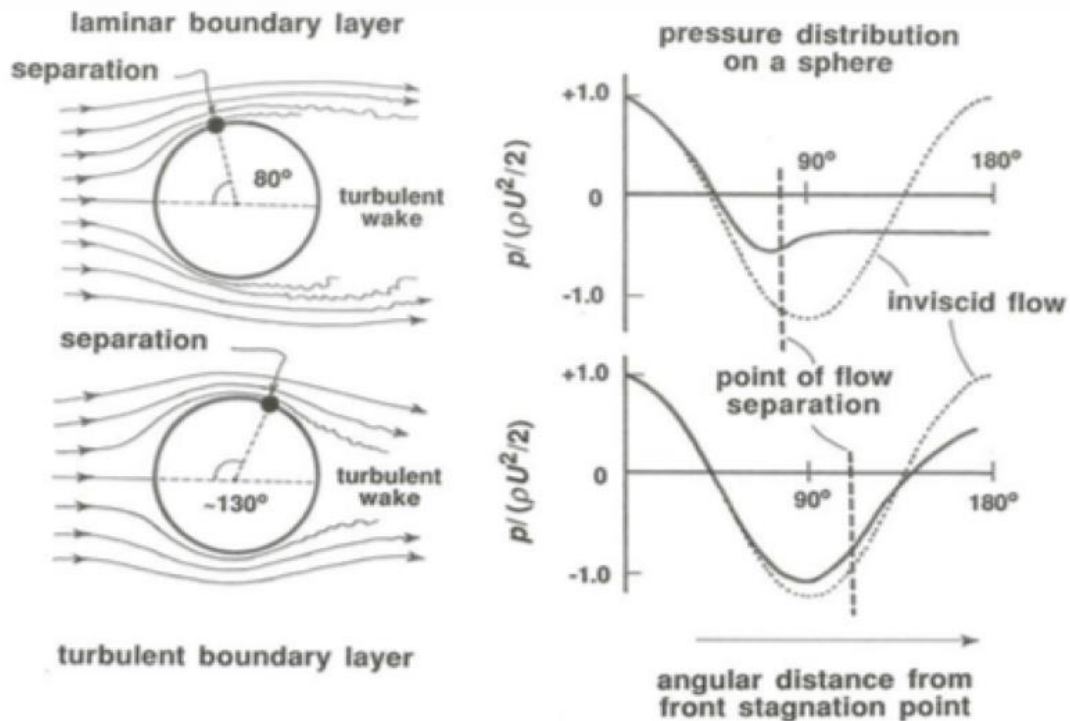


Figure 7

## Reynold's Number and Area

### Explanation

First, to explain the number, one must define "inertial force". This is a virtual force which is not a product of Newton's second law but is used to make the second law work. An example would make this clearer. For someone standing on the ground, stationary, a train and a car moving along (at say 50m/s) both these objects are moving but for one on board the train, the car isn't moving and the person on the ground is moving backwards--- the basic principle of Classical Relativity. Similarly, if the person starts to run and accelerates at  $1\text{m/s}^2$ , the same would be measured by the observer on the train but if the person then puts their hand out and touches the back of the train, the train will not feel a force (unless the person ends by travelling faster than 50m/s). If the person's hand is "sticky" (has an adhesive) (as fluid molecules tend to be) then the force will be in the opposite direction to the person's acceleration's direction but the force is reducing. For the force, one would have to (based on adhesion) have to subtract the momentum (mass\*velocity) from the force, if one is to find the value in the lab frame; this is the inertial force thus  $\rho \cdot v$  is at the numerator.

*One may also want to turn it into mass...*

As for the viscosity term, it measures how much the fluid can transfer energy throughout itself; the more it can the smaller the number and the more each particle maintains a higher velocity (the more quickly the fluid can move).

Regarding the specific setup, once the fluid's cross half the sphere:

There is no object to divert the flow tangential to the sphere (like there was prior to the crossing of half the sphere) thus the fluid has been forced to the edges; without any force, there would be a cylindrical hole in the rest of the flow but since water molecules move to the edge (greater " $r$ "—radius as a position vector) push the ones closer to the center, they cause a pressure gradient. As in the first term (on the right hand side, which is implied for the rest of the terms referred to) of the Navier-Stokes equation, the particle experiences a force down the pressure gradient—i.e. towards the center of the cylinder. This is why that volume is covered. This also explains why as  $r$  increases,  $F$  decreases (as there are fluids at smaller  $r$ s too thus pressure exists at smaller  $r$ s so the gradient is smaller (rate of change doesn't drop to 0)).  $R_e$  connection

The inertial terms also have another effect: they also shows the momentum that acts on a molecule if it stops thus a higher Reynold's number will mean more energy for a particle which stops which does not have to travel in a parallel direction; the viscosity is how much it will go in a parallel direction.

$\rho g h$  for stationary fluids only; since we ignore gravity that doesn't matter. But velocity influences<sup>1</sup>.

**Pressure**-caused velocity change increases with time so, based on how fast the fluid is (greater pressure). Eventually,  $v_{\text{particle}} \perp v_{\text{laminar}}$ .

Opposite streams collide; since there is already water in front, they go back. Etc. Thus the vortices form.

Greater velocity of fluid,  $\rho$  or more fluid (" $h$ "), more pressure is applied in  $-r$  direction. There is also (relatively) less viscosity for parallel flow velocity to be transmitted to chaotic areas.

Hence greater  $R_e$  causes greater pressure so more and more fluid is pushed inside thus takes more "area" so area of turbulence is increased.

<sup>1</sup>Imagine a surface (membrane) blocking the flow; there will be acceleration and impulse.

As implied above, the greater the diameter the greater the pressure (as there would be more fluid, effectively a height term in  $\rho g h$ ), thus greater " $L$ " will cause greater inward force due to the pressure adding with "height".

## Viscosity

**Explanation-** Considering a fluid, with a shearing force acting on the top of it, thus the fluid (specifically the particular horizontal layer the force is acting on) is displaced by some amount. The more the total displacement per time, the more the viscosity, the less this value

$$\begin{aligned}
\text{units}(\mu) &= Pa * s \Rightarrow \mu = (\text{constant}) * P * t \\
\mu &= \vec{F} \div x = m\vec{u}' \div (\text{Area}/t) \\
\text{Area}/t &= \frac{dA}{dt} = \frac{d}{dt}A \\
&= \frac{d}{dt} \int_0^{h=Y} \text{displacement } dy \\
&= \frac{d}{dt} \int_0^{h=Y} \int_0^T \vec{v} dt dy \\
&= \left( \int_0^{h=Y} \int_0^T \int_0^y \frac{\partial \vec{u}}{\partial y} dy dt dy \right)' \\
&= \int_0^{h=Y} \vec{u} dy
\end{aligned}$$

This last equation is the 'sum' of velocities over each layer of the liquid; define that to equal " $\vec{V}(t, \text{etc.})$ ", turn into acceleration hence  $\vec{A}(t, \text{etc.})$ . Basically, the total effect of the shearing force till that point in time.

#### The Navier-Stokes Equation

$$\rho \frac{d\mathbf{u}}{dt} = -\nabla P + \mu \nabla^2 \mathbf{u} + \sum \mathbf{F}$$

Some general expressions' definitions

Assumptions: • Viscosity does not change with force [ $\partial \mu = 0$ ];  $\partial F$  • The fluid does not disappear or appear from anywhere (there is no source "i" in the exponent or subscript, with one "up" and the other "down" implies a summation over i.

$$\begin{aligned}
\vec{e}_{x_i} &= \text{basis vector in } x_i \text{ direction} \\
x_n &= x_1, x_2, \dots, x_N; \quad 1 \leq m \leq N
\end{aligned}$$

$$\frac{df}{dx}(x) = \lim_{h \rightarrow 0} \frac{f(x+h) - f(x)}{h} \quad (2)$$

$$\frac{\partial f}{\partial x_m}(x_n) = \lim_{h \rightarrow 0} \frac{f(x_1 \dots x_m + h \dots x_N) - f(x_n)}{h} \quad (3)$$

$$\nabla = \sum_i e_{x_i} \frac{\partial}{\partial x_i} \quad (4)$$

$$\nabla(S) = \sum_i e_{x_i} \frac{\partial S}{\partial x_i} \quad (5)$$

$$\vec{v} = \sum_i v^i e_{x_i} \quad (6)$$

$$\vec{v} \cdot \vec{w} = \sum_i v^i w^i \quad (7)$$

$$\nabla^2 S(Input_n) = \nabla \cdot \nabla S = e_{x_i} \frac{\partial^2 S(\dots)}{\partial x_i^2} = \sum_i \frac{\partial^2 S(\dots)}{\partial x_i^2} \quad (8)$$

## Divergence

### Formula

$$\nabla \cdot \mathbf{v}(x_n) = \sum_{i=1} \frac{\partial}{\partial direction_i} v^i$$

Note:  $\vec{a} \cdot \vec{b} = \sum_{i=1} a^i b^i.$

A divergence operator takes in a vector field and gives out a scalar field which, at any point, is equal to the sum of the magnitudes of the vectors (in a small ( $\lim_{r \rightarrow 0}$ ) circle around the point, except the vector at the point) pointing towards it subtracted from the sum of the magnitudes of the vectors (in a small ( $\lim_{r \rightarrow 0}$ ) circle around the point) pointing away from it. One can understand it as, in terms of fluid flow, how much of a source or a sink the point is; the Navier-Stokes equation assumes the liquid is incompressible; divergence equals zero. As for how the formula gives this, it adds up the rate of change of each component as it moves in its direction; if it is positive, that means that the 'going out' (vector component of the point) is less than the one 'in front' (in the positive direction of the component) and more than the one just behind (as we assume the function is differentiable (not sharp—smooth) at the point in the question for the divergence of the function to act on) and since  $h$  can be positive or negative. The opposite is true for negative output and 0 means the amount going in is the same as the amount goes in as comes out; incompressible field. As it's done for all components, the value in all dimensions is added up and a clear picture of all directions is formed.

### Terms of Navier-Stokes

Beginning with the term on the left hand side, it is similar to  $F = ma$ .  $\rho$  is the density of the object; density is preferred to mass as, due to incompressibility and the fact that the equation is regarding each point, almost (rather a volume that approaches zero), the volume is constant but mass is too small; density is a more concrete value to use. As volume is constant, the volume reciprocal is just a scaling factor which we can simply alter units for; the density of a fluid is also relatively easy to look up and is constant; finding the mass would require an extra step of multiplying by volume. The

second term is just the temporal partial derivative of velocity— ie. acceleration<sup>1</sup>. It can be broken down into 4 other derivatives too by the multivariable chain rule:

$$\frac{df}{dt}(x_n(t)) = \sum_n \frac{\partial f}{\partial x_n} \frac{\partial x_n}{\partial t} \quad (10)$$

$$\frac{d\vec{u}}{dt}(t, x, y, z) = \frac{d\vec{u}}{dt}(t, x(t, ..), y(t, ..), z(t, ..)) = \frac{\partial \vec{u}}{\partial t} \frac{dt}{dt} + \frac{\partial \vec{u}}{\partial t} \frac{\partial \vec{u}}{\partial x} + \frac{\partial \vec{u}}{\partial t} \frac{\partial \vec{u}}{\partial y} + \frac{\partial \vec{u}}{\partial t} \frac{\partial \vec{u}}{\partial z} \quad (11)$$

$$= \frac{\partial \vec{u}}{\partial t} + (\nabla \cdot \vec{u}) \frac{\partial \vec{u}}{\partial t} \quad (12)$$

The first term on the right hand side is the negative pressure “gradient”. The negative pressure gradient gives fastest spatial descent of the pressure; the direction to travel from any given point to reduce the pressure the most. Force acts this way as a high pressure region will push a particle to a low pressure region.

The second term is trickier. It is basically the viscosity of a given fluid multiplied by how much more speed<sup>2</sup> its neighbors have;  $\mu$  is the viscosity\*. The other term is the Laplacian of the velocity field. This means that it first takes the vector in 3 components (since velocity, spatially, is 3 dimensional) then takes the scalar Laplacian of each. This means it first gives the direction in which to move to have the component increase the most; then it gives the divergence of this value and arranges them in vector form.

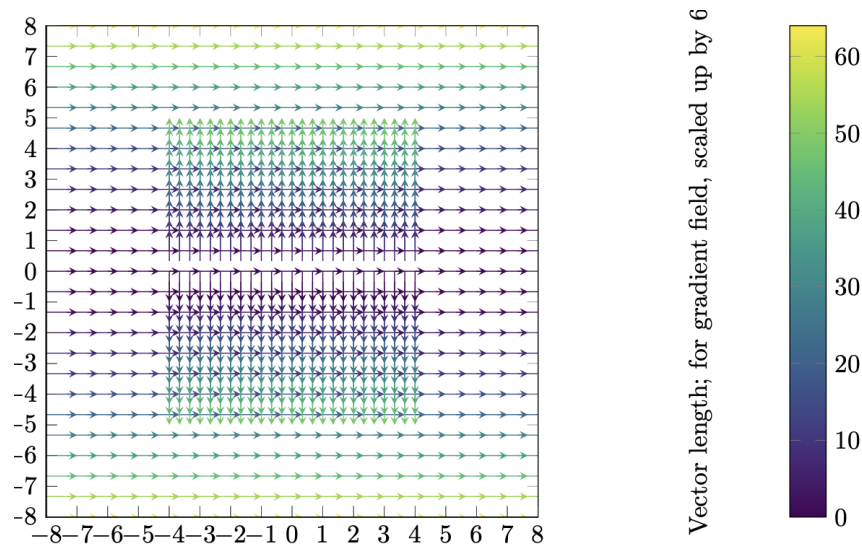
$$\nabla^2 \vec{v}(x_n) = \sum_n e_{x_x} \nabla^2 v^n$$

This can be written in column vector format by placing each individual term in the summation in its own row, going in ascending order of n.

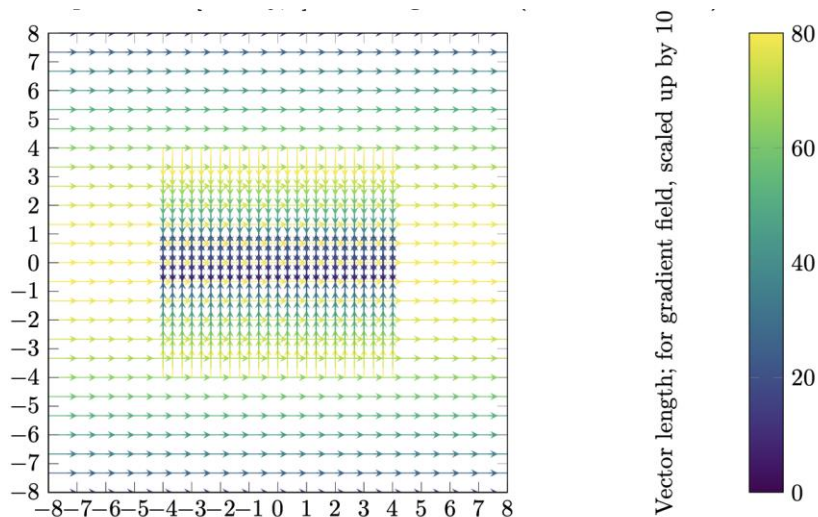
<sup>1</sup>Usually, "ma" is written as  $\frac{dmv}{dt}$  or  $m \frac{dv}{dt}$ .

<sup>2</sup>Related to kinetic energy.

Diagrammatic aid, using some vector fields:

**(Diverging) x-Component of  $[(y + 3)^2, 0]$  and its Gradient (Smaller Domain)****Figure 8**

The vector field of the gradient diverges at (0,0) thus the Laplacian of the x component is positive.

**(Converging) x-Component of  $[80 - 2y, 0]$  and its Gradient (Smaller Domain)****Figure 9**

These vector fields are solely for  $\nabla^2 u_x$  thus only their length matters (since they all face the same direction).

Viscosity/  $\mu$ : how "sticky" the liquid is (rather how hard it is to move); how little (or much) it transfers the force throughout. Thus viscosity/  $\mu$  is how cohesive or not cohesive the fluid is. Molecules interact, due to forces, with other molecules that are not on their path; how strong that interaction is described by viscosity. If viscosity is low, molecules from a high speed area will transfer that speed to molecules of a low speed area around them at a quick rate (definition of high force); if viscosity is high the opposite will happen. As for the second graph, since divergence of  $u$  is negative, it is transferring its velocity away meaning its velocity is reducing so force has to be negative of the velocity: if it transfers

quickly (low viscosity), the magnitude of the force is high; if slowly (high viscosity), the magnitude of the force is low. The direction of this gain in velocity is the same as the one where the neighbors have more or less of it thus  $u$  is multiplied by the corresponding  $\vec{e}_i$ .

As for the last term, it is merely the other miscellaneous forces being added on (usually just gravity so usually written as  $pg$ ).

### Summary

It simply states that the force equals the sum of the (net) pressure acting on it, the forces induced by the other molecules (based on viscosity) and the other "miscellaneous" forces (usually gravity).

### Variables

Controlled: fluid velocity, kinematic viscosity, diameter of sphere, material of sphere

Dependent: the area of non-streamlined disturbed region beyond the sphere

Independent: Reynolds number

How to calculate Reynolds number (independent variable )

-Reynolds number = (fluid velocity x internal diameter)/ kinematic viscosity

How perturbed area is measured (dependent variable )

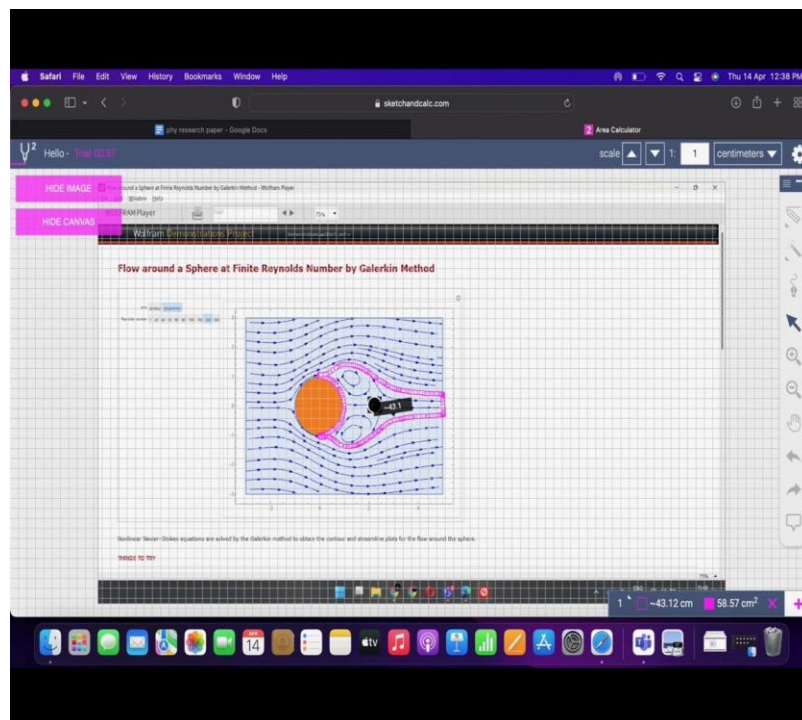


Figure 9

We measured the area of dependent variable with the help of an application that helps you to find the area of it easy by using the unit square method which divide the shapes into unit squares. Total unit squares falling within the shape determines the total area.

### Controlled Variable

Fluid velocity: in order to keep fluid velocity constant, a water flow regulator can be used to keep velocity constant

Kinematic viscosity and type of fluid: the fluid used and the atmospheric pressure should be constant in order to keep these variables constant.

The same sphere should be used while carrying out all experiments. No external forces should be acting upon it. Diameter of sphere has to be constant for reliable results of Flow around a Sphere at Finite Reynolds Number by Galerkin Method.

### Authentication of Simulation

The simulation is created by Mikhail Dimitrov Mikhailov is a highly respected and renowned lecturer who has collaborated with various researchers around the globe including contributions to being called for multiple international meetings to portray his primary based research on “flow around a sphere at finite Reynold’s numbers in presence of streamlines of the fluid around the sphere”. Mikhail was also a teacher at the Technical University of Sofia where he taught thermodynamics and heat transfer in immense depth.

This simulation was posted by Mikhail Dimitrov Mikhailov in 2015 on the website <https://demonstrations.wolfram.com/FlowAroundASphereAtFiniteReynoldsNumberByGalerkinMethod/>

It is a trusted website created by Stephen Wolfram the founder of this website who is also a scientist and has written 23 books on mathematics and computer sciences. Stephen Wolfram was a child genius who gave a platform to people like Mikhail to portray their simulations with 100% credits.

### Data Collection

The data is divided into 2 parts,

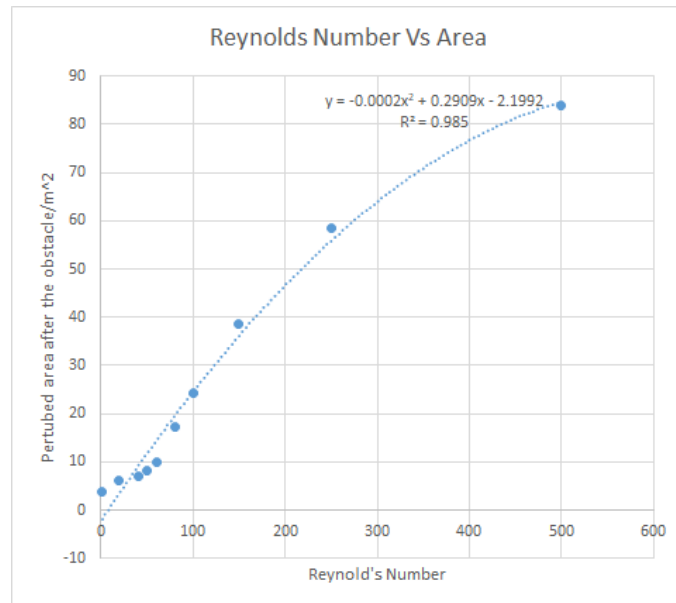
- The first aspect measures the change in the perturbed area of the flow around the sphere with a change in the Reynolds number. It is used to show the effect on the perturbed area as the Reynolds number of the fluid increases by measuring the area at Reynolds numbers within the range of 1 and 500; a graph is plotted for the same.
- The second aspect measures the effect of the Reynolds number of the fluid on the flow separation angle – both on the top and the bottom in order to get an average flow separation angle and a graph of the Reynolds number and the average flow separation angle is plotted to graph the relationship between them.

**Table 1**

Reynolds Number /	Area / m <sup>2</sup>	Ln (Reynolds Number) no Unit	Ln (Area)/ m <sup>2</sup>
1.0	3.9		
20.0	6.0	3.0	1.8
40.0	6.9	3.7	1.9
50.0	8.2	3.9	2.1
60.0	9.9	4.1	2.3
80.0	17.1	4.4	2.8
100.0	24.4	4.6	3.2
150.0	38.7	5.0	3.7
250.0	58.6	5.5	4.1
500.0	84.0	6.2	4.4

The above data is collected from the simulation, it is observed that as the Reynolds number increases the perturbed area beyond the obstacle increases. The variation is not in a linear sense.

### Analysis



**Figure 10**

The graph initially seems to be linear and then the gradient of the graph decreases. There are few points initially which are very close to each other which gives the indication that as the Reynolds number increases, the perturbed area (disturbed area) also increases. The initial increases in Reynold's number does not have much effect on the perturbed area after the obstacle when the Reynold's number is around 100 the streamline flow is maintained, there is no turbulence generated. So water flowing around the obstacle, there is a flow separation of the water layers and the separation are very close to the rear of the sphere.

The streamline converges more slowly at the back of the sphere than diverge at the front. So the front to back pressure forces to increase more rapidly than predicted by stokes law for the lower range of Reynold's number.

As the Reynold's number increases to the higher value from 80 to 200, we see a steep increase in the perturbed area. As at the higher Reynolds number, the point of separation moves towards the side of the sphere, it starts to oscillates and the flow increases turbulence, the area of perturbation will be higher.

From the graph we can infer that there is increase in the gradient around 100-300, that is when the Reynold's number is changed from the 80-250, the perturbed area increases drastically. After the Reynolds number of 250 we can observed the reduction in the gradient because the drag is observed on the sphere due to pressure distribution and small contribution from the viscous shear stress.

### To Analyze the Data Further

$$A \propto \text{Re}^n$$

$$A = k \text{Re}^n$$

Take log both the sides

$$\text{Ln}^a = \text{Ln}k + n \text{Ln Re}$$

Compare the below graph  $y = mx + c$

To find the relation between the variable, need to plot  $\text{LnA}$  v/s  $\text{LnB}$

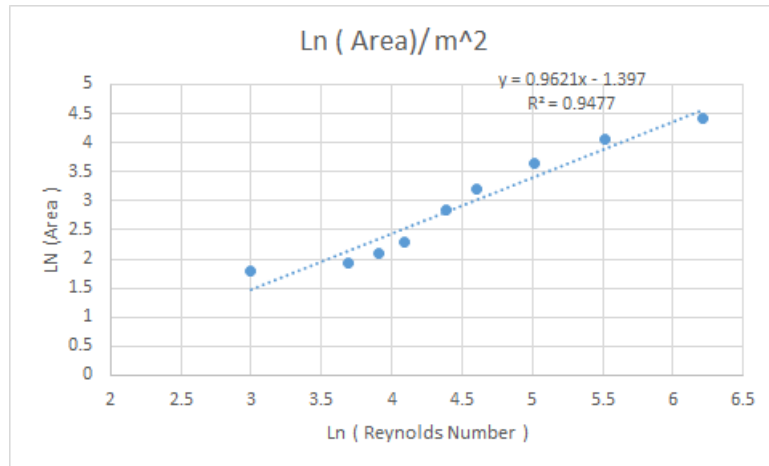


Figure 11

- The above data shows that as the Reynolds number increases, the area of the perturbed area of the flow around the sphere increases, plotting a positive logarithmic curve with the equation:  $y = -0.0002x^2 + 0.2909x - 2.1992$

Table 2

Reynolds Number	Flow Separation Angle- Top	Flow Separation Angle- Bottom	Average Flow Separation Angle	LN (Reynolds Number)	LN (Average Flow Separation)
1.0	145.0	145.0	145.0		
20.0	139.0	135.0	137.0	3.00	4.92
40.0	130.0	125.0	127.5	3.69	4.85
50.0	125.0	125.0	125.0	3.91	4.83
60.0	110.0	130.0	120.0	4.09	4.79
80.0	95.0	110.0	102.5	4.38	4.63
100.0	90.0	110.0	100.0	4.61	4.61
150.0	105.0	85.0	95.0	5.01	4.55
250.0	90.0	100.0	95.0	5.52	4.55
500.0	85.0	85.0	85.0	6.21	4.44

The above data is collected from the simulation; as the Reynolds number increases, the average flow separation angle of the flow around the sphere decreases. The decrease is not linear.

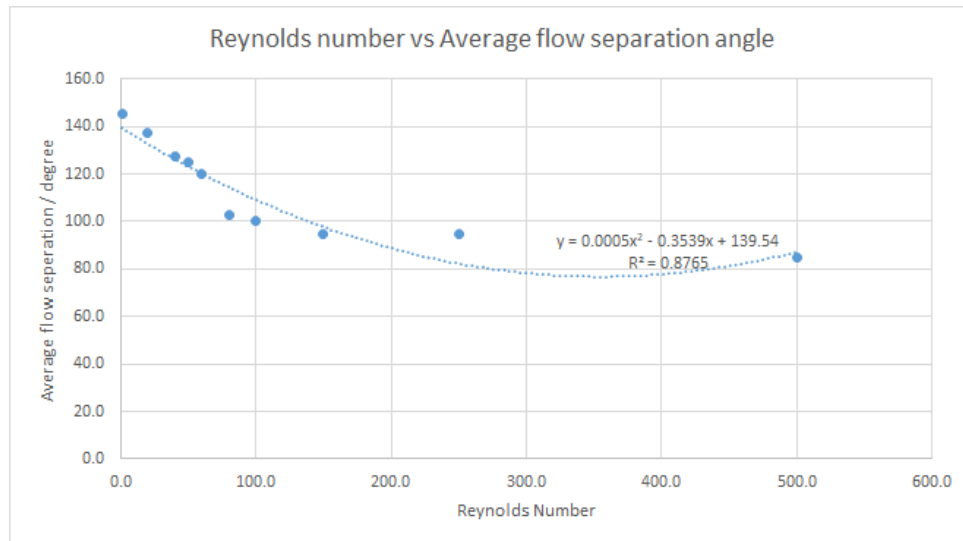


Figure 12

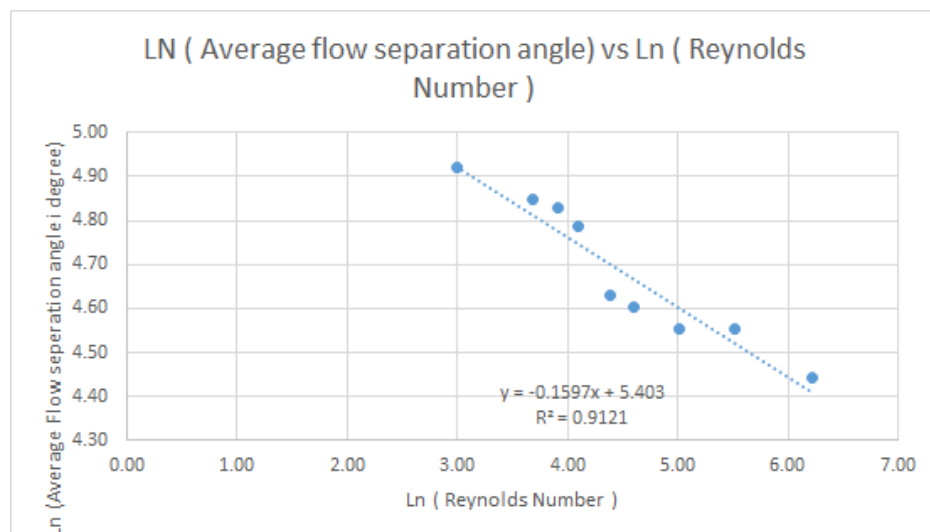


Figure 13

Initially, the graph has a steeper negative gradient which decreases its slope as the Reynolds number progressively increases. This demonstrates that changes in lower Reynolds numbers, cause a drastic change in the average flow separation angle, however, the extent of change of the average flow separation angle decreases at higher Reynolds numbers. The reason for the decrease in the average flow separation angles as the Reynolds number increases is due to the fact that as the Reynolds number increases, the inertia effects are more domineering than the viscous effects, hence causing the boundary layer to separate from the sphere faster than before.

For Reynolds number 150 and 250, the average flow separation angle is constant, however, with distinct differences in its top and bottom flow separation angle. These large differences in the top and bottom flow separation angle is more prevalent at higher Reynolds numbers – over Reynolds number 60. At lower Reynolds numbers, the symmetry of the flow around the sphere is relatively uniform; this is reflected in the data regarding differences in the top and bottom flow separation angles.

In general, the data shows an increasing difference between the top and bottom flow separation angle as the Reynolds number increases, indicating that as the Reynolds number increases, the symmetry of the perturbed area decreases. This however, does not apply for the Reynolds number of 500 which has an equal top and bottom flow separation angle.

## EVALUATION

As the data is collected using the simulation, there is possibility of the errors if the same experiment is performed in the real life. One needs to explore the simulation assumptions which may have affected the values of perturbed area.

The following assumptions

- Stabilizing of the sphere, if the sphere in the liquid is not stable unlike in the simulation then it would affect the perturbed area and difficult for measuring the area accurately or measuring the flow separation angle. To avoid that in real life we need to keep the attached rigidly to the surface to avoid wobbling.
- Identifying the perturbed area will be difficult in the real life as the path of the after molecules may be random and camouflage with the perturbed area. So to avoid that one need to take the video of the steam flowing after the sphere and identify the actual perturbed, in the simulation it was an easy task to do.
- Due to the viscosity of the water though it is low still it may have an impact on the perturbed area or the flow separation angle, as the liquid layers might be at different speed which may not be considered by the simulation. It might affect the area which is disturbed. To avoid that need to reduce the viscosity so that the results might be nearly accurate.
- $g=0$ ; As seen in Navier-Stokes, gravity is an important term in force thus in acceleration thus velocity thus position. The effect of a gravitational field would mean that liquids at the top move quicklier to the center and fluid at the bottom will move up slower (if at all, based on strength of gravity and pressure). This can be corrected using high pressure or a low gravitational field.
- In real life, when the experiment is performed, the moving wind over the liquid surface will add an inertial effect on the layer of the liquid which may affect the perturbed area. To avoid this, we need to consider a sealed environment where there is no air flow.
- The simulation considers that the water flow as a laminar flow which is not subject to any frictional forces. In real life, to eliminate the frictional forces completely is difficult. In order to avoid this, before changing the Reynolds number, measure the perturbed area and consider this area as the background area. Hence, when the Reynolds number is changed again, this area must be subtracted from the perturbed area to ensure this does not affect results.

## CONCLUSIONS

The aim of this research paper was to determine how the finite value of Reynolds number of the liquid affects the perturbed area and the flow separation angle for a constant liquid and object. The paper made use of a simulation of the flow around a sphere with changing Reynolds numbers. Data was taken from the simulation for the perturbed area and flow separation angle, and was analyzed and evaluated to determine the effect of the Reynolds number on the mentioned factors. In

general, the paper came to the conclusion that, as the Reynolds number increased, the data showed an increase in the perturbed area and a decrease in the flow separation angle, with a decrease in symmetry of the perturbed area as the Reynolds number increased.

As per the graph of the Reynolds number and the average flow separation angle, it indicates that they have an inversely proportional relationship, though the relationship is quite weak. It indicates that as the Reynolds number increases,  $\theta$  decreases.

$$\theta \propto r^{-2}$$

The reason for this inverse relationship between the Reynolds number and the flow separation angle is that as the Reynolds number increases, the viscous effects are continually overshadowed by the inertia effects, causing the boundary layer of the fluid to separate from the sphere quicker and causing a decrease in the flow separation angle.

As per the graph of the Reynolds number and the perturbed area, it indicates that they have a directly proportional relationship. It indicates that as the Reynolds number increases, the perturbed area of the flow around the sphere also increases.

$$A \propto r^{0.95}$$

$$A \propto 0.9621r$$

The reason for this direct relationship is that as the Reynolds number increases, the point of separation changes, increasing the turbulence of the flow, resulting in an increase in the perturbed area of the flow around the sphere with an increase in the Reynolds number. This increasing turbulence is also a cause of the decrease in symmetry of the perturbed area as the Reynolds number increases.

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